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# QW diode laser modulation by lateral gain tailoring

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**Abstract.** We present a new modulation technique by the control of lateral modal gain profile in four-terminal stepped-mesa diode laser. The simulation of the high frequency laser characteristics is performed on the basis of a computer model of stripe geometry diode laser which takes into account lateral effects. Modulation bandwidth of 11 GHz for ridge laser can be extended for 5–6 GHz by employing a newly developed stepped-mesa laser design. Moreover, nearly flat small signal modulation response with 3 dB bandwidth as high as 38 GHz can be obtained by making use of modulation of the lateral gain profile.

## Introduction

Nowadays, very high speed diode lasers are required to satisfy the rapid increase in transmission speed of long haul fiber optic network. Long (1.3 $\mu$m or 1.55 $\mu$m) wavelength semiconductor lasers with 30 GHz direct modulation bandwidth were recently reported [1]. Several attempts to further increase the 3 dB bandwidth under direct modulation were made [2, 3] using specially designed MQW structures. Structures with optimized MQW profile and doping levels were suggested and bandwidth of 40 GHz was obtained for devices lasing at 1.1 $\mu$m [2]. Tunneling injection lasers on 0.98 $\mu$m emission wavelength were proposed and 3 dB bandwidth of 48 GHz was demonstrated. However, it is hardly possible to significantly improve the direct modulation bandwidth by further optimization of the MQW structure design. Use of other modulation schemes such as push-pull modulation [4], reflection coefficient modulation [5] or confinement factor modulation [6] allows to improve the modulation performance with respect to direct modulation. In this paper we report on the design and high frequency performance of novel four-terminal stepped-mesa diode laser.

## 1 Laser design

The device is designed on the basis of the ridge laser with two additional side electrodes used for confinement factor modulation [6]. The laser is a multiple quantum well structure containing three InGaAsP ($\lambda = 1.3$ $\mu$m) QWs 1% compressive strained and four InGaAsP ($\lambda = 1.1$ $\mu$m) barriers lattice matched to InP. Fabry–Perot cavity is 150 $\mu$m long and has two cleaved mirrors with reflectivity coefficients of about 0.32. Central electrode, 2 $\mu$m wide, is surrounded by 1.5 $\mu$m wide stairs etched in upper cladding. The central contact is for pumping and/or direct modulation and side electrodes are for applying additional bias and/or modulating signals. The schematic representation of four-terminal stepped-mesa diode laser is depicted in Fig. 1. The main advantage of the laser geometry is the specific stepped-mesa profile of central electrode which allows to maintain specific lateral profile of the optical gain. The lateral overlap of injected carriers with the optical mode profile can be substantially increased with respect to traditional ridge or buried laser structures. This allows to improve the high frequency laser performance even under direct modulation. The use of additional side electrodes leads to tailoring of lateral shape of modal gain at

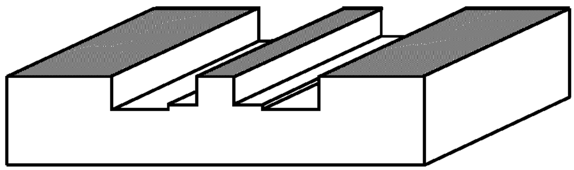

**Fig. 1.** Schematic representation of four-terminal stepped-mesa laser diode.

high speed. Direct modulation regime as well as modulation by the signal applied to the side electrodes can be realized in this structure. By using two simultaneous signals applied to the central and to the side electrodes, the output power waveform correction can be performed [6].

## 2 Results and discussion

The analysis of the laser operation is done using the computer model of laterally nonuniform ridge laser. This model accounts for all lateral effects which take place in a typical ridge laser such as lateral pumping current spreading in contact and upper cladding layers and carrier drift and diffusion in undoped SCH and MQW layers. The model includes in a phenomenological way the processes of carrier capture and escape in/out of QWs.

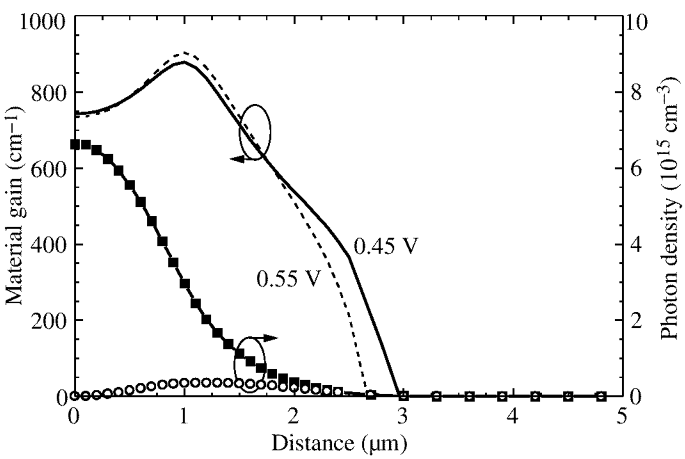


**Fig. 2.** Lateral distributions of material gain (lines) in four-terminal stepped-mesa structure at different voltages applied to the side contacts. The photon densities in zero- (solid symbols) and first-order (open symbols) lateral modes correspond to 0.55 V side voltage.

Due to the axial symmetry, the simulations are performed only for the right-hand side of the laser structure and then the lateral distributions obtained are extended to the whole device to calculate the total output power. The lateral distribution of material gain at different bias applied to the side contacts is plotted in Fig. 2. The photon density profiles in zero- and first-order lateral modes are also presented in Fig. 2. The mode profiles are assumed to be fixed by the index steps in deeply etched mesa structure and independent of pumping and side bias. As can be seen in this figure, lateral gain profile changes with the side voltage in very special manner. In the center of the mesa ($x = 0$) high photon density drastically reduces the effective carrier lifetime leading to the clamping of the carrier density. Due to this the material gain also becomes fixed in the center of the mesa. The gain is allowed to

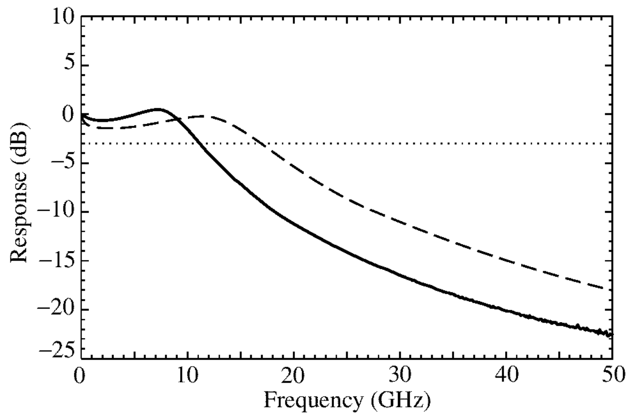


**Fig. 3.** Simulated small signal direct modulation responses of simple ridge (solid) and stepped-mesa (dash) structures.

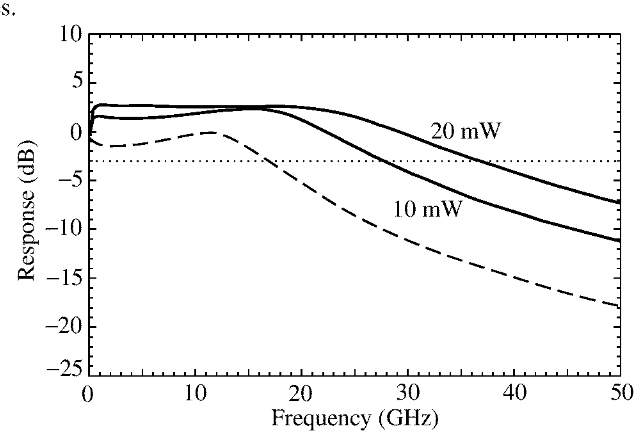


**Fig. 4.** Simulated small signal responses of a stepped-mesa structure under modulation by the side voltage (solid) at different output power levels. Direct modulation response at 10 mW (dash) is shown for comparison.

change only in the areas under the steps of the mesa. The proper design of the width and height of these steps results in a very efficient lateral gain tailoring by the side voltage.

Fig. 3 shows the small signal direct modulation responses for two cases of laser geometry. The first is a simple 2 $\mu$m wide ridge and the second is a stepped-mesa etched to the same depth as the ridge. It is clear from Fig. 3 that direct modulation bandwidth improves in stepped-mesa device, which is due to lateral redistribution of the injected carriers. The 3 dB bandwidth of 11 GHz in ridge laser can be extended for 6 GHz by using the stepped-mesa structure.

The high speed performance of a stepped-mesa laser improves significantly when the modulating voltage signals are applied to the side electrodes. The comparison of simulated small signal responses under direct (pumping current) and side voltage modulation is presented in Fig. 4. The cut-off frequency of 28 GHz is achieved at 10 mW output power under the modulation of the lateral gain distribution, while the direct modulation bandwidth is only 17 GHz. At higher output power, the 3 dB bandwidth of 38 GHz is obtained.

## 3 Summary

We have analyzed the design features and high frequency performance of a four-terminal stepped-mesa diode laser. It is shown that with the use of stepped-mesa structure the intrinsic response of the laser can be extended towards higher frequency even under direct modulation. The modulation by the signals on side electrodes of the device results in a very broad modulation bandwidth by means of lateral gain tailoring. The modulation response with 3 dB bandwidth as high as 38 GHz can be obtained on the structure initially having only 11 GHz cut-off frequency.

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